Design of improved controller for thermoelectric generator used in distributed generation

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ABSTRACT

This paper investigates the application of thermal generation based on solid-state devices such as thermoelectric generators (TEGs) as a novel technological alternative of distributed generation (DG). The full detailed modeling and the dynamic simulation of a three-phase grid-connected TEG used as a dispersed generator is studied. Moreover, a new control scheme of the TEG is proposed, which consists of a multi-level hierarchical structure and incorporates a maximum power point tracker (MPPT) for better use of the thermal resource. In addition, reactive power compensation of the electric grid is included, operating simultaneously and independently of the active power generation. Validation of models and control schemes is performed by using the MATLAB/Simulink environment. Moreover, a small-scale TEG experimental set-up was employed to demonstrate the accuracy of proposed models.

1. Introduction

In the last decade, problems related to energy factors (oil crisis), ecological aspects (climatic change), electric demand (significant growth) and financial/regulatory restrictions of wholesale markets have arisen worldwide. These difficulties, far from finding effective solutions, are continuously increasing, which suggests the need of technological alternatives to ensure their solution. One of these technological alternatives is known as distributed generation (DG), and consists of generating electricity as near as possible of the consumption site, in fact like it was made in the beginnings of the electric industry, but now incorporating the advantages of the modern technology [1]. Here it is consolidated the idea of using clean non-conventional technologies of generation that use renewable energy sources (RESs) that do not cause environmental pollution, such as wind, solar (photovoltaic and thermal), hydraulic, among others [2].

Recently, a rising interest on thermal generation based on solid-state devices such as thermoelectric generators (TEGs) has emerged as a feasible option of generation of clean energy, mainly because of the development of new semiconductor materials and of their commercial availability in the existing open markets [3,4].

TEGs allow generating electricity directly and with no moving parts from a temperature difference held across the junction of two dissimilar semiconductor materials. These devices share the major characteristics of photovoltaic (PV) systems, being their advantages the possibility of generating electricity continually while they are provided of heat and the significant reduction of costs, reaching today the sixth part of a PV system. Consequently, TEGs are presently arising as
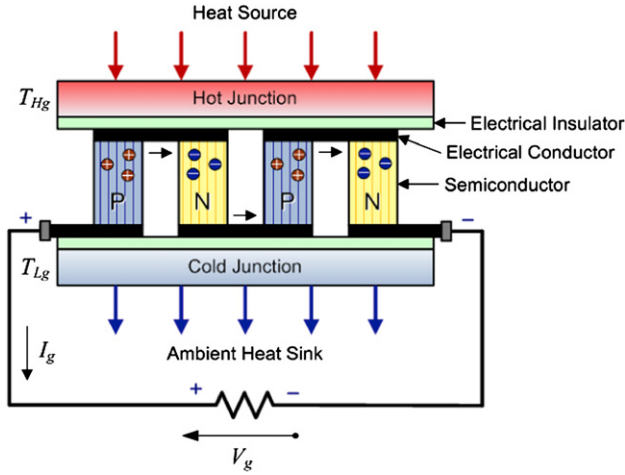
Fig. 1 – Schematic diagram of the TEG.

a new option inside the portfolio of renewable energy sources and are becoming serious candidates for applications in DG.

Based on the stated above, the present work proposes the application of this novel technological alternative in distributed generation systems. The development of the TEGs integrated into the distribution power grid is presented and the analysis of the dynamic performance of the device and the impact of its use in electric system are included. This work comprises the detailed modeling of TEGs and the power electronic interface with the electric system, as well as the design of the control scheme of the global system.

2. Modeling of the proposed TEG system

Two commercially available thermoelectric generators are experimentally studied for the proposed system, the Hi-Z and Tellurex TEG modules [5].

The schematic diagram of the thermoelectric generator is shown in Fig. 1. A TEG consists of two dissimilar materials, n-type and p-type semiconductors, connected electrically in series and thermally in parallel. Heat is supplied at one end, i.e. the hot junction, at a temperature T_{Hg}, while the other end, that is the cold junction, is maintained at a lower temperature T_{Lg} by a heat sink. As a result of the temperature difference, an output voltage V_g is generated so that a current I_g flows through an external load resistance. The power output depends upon the temperature difference, the properties of the semiconductor materials and the external load resistance.

For the heat conduction effect, the Joulean heat and the energy supply or removal to overcome the Peltier–Seebeck effects are combined for the whole generator arrangement. The rate of heat supply Q_{Hg} and heat removal Q_{Lg}, the output generated voltage V_g, the net output power P_g and the thermal efficiency η are given by Eqs. (1)–(5), as follows [6]:

The rate of heat supply,

$$Q_{Hg} = \alpha_g I_g T_{Hg} - 1/2\, I_g^2 R_g + k_g(T_{Hg} - T_{Lg}) \tag{1}$$

The rate of heat removal,

$$Q_{Lg} = \alpha_g I_g T_{Lg} - 1/2\, I_g^2 R_g + k_g(T_{Hg} - T_{Lg}) \tag{2}$$

The output voltage,

$$V_g = \alpha_g(T_{Hg} - T_{Lg}) - I_g R_g \tag{3}$$

The net output power,

$$P_g = \alpha_g I_g(T_{Hg} - T_{Lg}) - I_g^2 R_g \tag{4}$$

and the thermal efficiency,

$$\eta = \frac{P_g}{Q_{Hg}} \tag{5}$$

Fig. 2 depicts the equivalent circuit of a TEG single thermocouple composed of a thermal generated voltage source and a series intrinsic resistance. TEG thermocouples are grouped together in larger units known as TEG modules or arrays, which are electrically combined in series and stacked in parallel to provide the desired output voltage and current. The equivalent circuit for the TEG thermocouples arranged in N_p-parallel and N_s-series is extended from the single model, as shown in Fig. 2.

Fig. 3 depicts the measured output power versus current curves, for a HZ-20 TEG (19 W/30–250 °C) tested in the laboratory for various T_{Hg} and T_{Lg} but maintaining the same temperature gradient of about 200 W. As can be clearly observed, there exists a strong parabolic dependence of power on the temperature difference across the module. As can be also noted, the internal resistance of the TEG varies with the temperature of the series evaluated, so that for providing maximum power to the load and thus optimizing the efficiency of the TEG system working with a variable thermal source, a continuous matching of the load resistance to the internal resistance will be demanded. This requirement turned out to be in a continuous adjustment of the thermocouple output terminal voltage.

3. Modeling of the power conditioning system

The main purpose of a grid-connected thermoelectric generating system used as a distributed generator is to transfer the
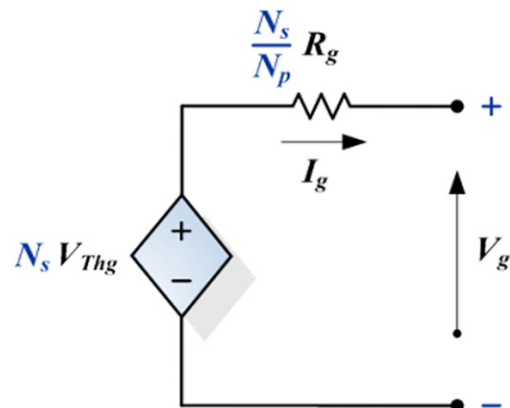

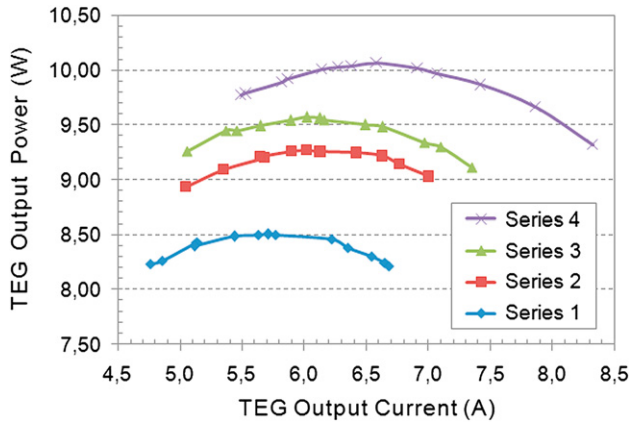**Fig. 2 – Equivalent circuit of a TEG thermocouple/array.**

Fig. 3 – TEG output power versus current for various T_{Hg} and T_{Lg}; Series No. 1: 260/60 °C, No. 2: 240/40 °C, No. 3: 230/30 °C and No. 4: 220/20 °C.

maximum power obtained from a heat source into the utility grid with a unity power factor. This goal imposes the necessity of being constantly operating the TEG system near the maximum power point (MPP) independently of the temperature gradient applied to the module and of the power exchanged with the electric grid; therefore the use of a maximum power point tracking controller (MPPT) is required. For grid-connected DG applications, two hardware topologies for MPPT have been mostly studied worldwide, known as one-stage and two-stage topologies. The first one connects the DG directly to the DC bus of a voltage source inverter (VSI), while the second topology employs a DC–DC converter (or chopper) as interface between the DG and the VSI. Since applications of modern distributed energy resources are enforcing new constraints of high quality electric power, flexibility and reliability to the RES-based DG; a two-stage energy conversion system topology has been proposed in this work for the present TEG application. This configuration of two cascade stages offers an additional degree of freedom in the operation of the grid-connected TEG system when compared with the one-stage configuration. Hence, by including the DC–DC boost converter between the TEG module and the power static inverter linked to the electric grid as shown in Fig. 4, various control objectives, as reactive power compensation, voltage control, and power oscillations damping among others, are possible to be pursued simultaneously with the TEG system operation without changing the PCS topology.

3.1. DC–DC boost converter

The intermediate DC–DC converter produces a chopped output voltage through pulse-width modulation (PWM) control techniques for controlling the average DC voltage relation between its input and output aiming at continuously matching the characteristic of the TEG array to the equivalent impedance presented by the DC bus of the inverter. This converter acts as an interface between the output DC voltage of the TEG modules, which is variable with temperature gradient applied across their junctions, and the DC link voltage at the input of the voltage source inverter, which is controlled to be kept constant at all load conditions. In this way, by varying the duty cycle of the DC–DC converter it is feasibly to keep constantly operating the TEG system near the MPP independently of both, the temperature difference conditions and of the load.

In order to deliver the required output DC voltage to the VSI link, a standard unidirectional topology of a DC–DC boost converter (also known as step-up converter or chopper) is employed. This switching-mode power device contains basically two semiconductor switches (a rectifier diode and a power transistor) and two energy storage devices (an inductor and a smoothing capacitor) for producing an output DC voltage at a level greater than its input DC voltage. The basic structure of the DC–DC boost converter, using an Insulated Gate Bipolar Transistor (IGBT) as main power switch, is shown in Fig. 4.

The steady-state voltage and current relations of the boost converter operating in continuous current conduction mode are stated by Eqs. (6) and (7), respectively.

$$V_d = \frac{V_A}{(1 - D)} \tag{6}$$

$$I_d = (1 - D)I_A \tag{7}$$

where

D, DC–DC converter duty ratio, $D \in [0, 1]$.
V_A, TEG array output voltage.
I_A, TEG array output current.
V_d, inverter DC bus voltage.
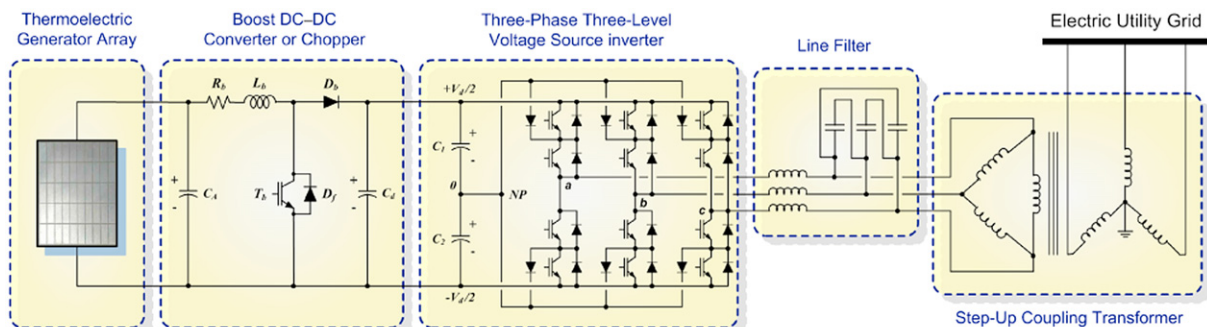I_d, inverter DC bus current.

Fig. 4 – Detailed model of the proposed grid-connected thermoelectric generating system.

3.2. Voltage source inverter

As the DC–DC converter acts as a buffer between the TEG array and the power static inverter by turning the temperature-dependent P–I characteristic curve of the TEG into a quasi-ideal thermal factor-controlled voltage source characteristic, the natural selection for the inverter topology is the voltage source (VSI). This solution is also the more cost effective one when compared with others like hybrid current source inverters.

The presented voltage source inverter (VSI) corresponds to a DC–AC switching power inverter using high-power fast IGBTs. This semiconductor device is employed due to its lower switching losses and reduced size when compared to other devices. In addition, as the power rating of the inverter goes from relatively low to medium, the output voltage control of the VSI can be efficiently achieved through sinusoidal pulse-width modulation techniques.

The VSI structure proposed is designed to make use of a three-level 12 pulse pole structure, also called neutral point clamped (NPC), instead of a standard two-level, 6 pulse inverter structure. Thus, the three-level pole attempts to address some limitations of the standard two-level by offering an additional flexibility of a level in the output voltage, which can be controlled in duration, either to vary the fundamental output voltage or to assist in the output waveform construction. This extra feature is used in this work to assist in the output waveform structure, generating a more sinusoidal output voltage waveform than conventional structures without increasing the switching frequency. In this way, the harmonic performance of the inverter is improved, also obtaining better efficiency and reliability.

The connection to the utility grid is made by means of a step-up Δ–Y coupling transformer, and second-order low pass sine wave filters are included in order to reduce the perturbation on the distribution system from high-frequency switching harmonics generated by the PWM control of the VSI. Since two ways for linking the filter can be employed, i.e. placing it before and after the coupling transformer, here it is preferred the first option because reduce notably the harmonics contents into the transformer windings, thus reducing losses as heat and avoiding its overrating.

The relation between the DC bus voltage V_d and the generated AC voltage V_{inv} in the utility side can be described by Eq. (8). This relation assumes that the DC capacitors voltages are balanced and equal to $V_d/2$.

$$V_{inv} = \frac{1}{2}maV_d \tag{8}$$

being,

m, modulation index of the VSI, $m_i \in [0, 1]$.
$a = \frac{\sqrt{3}}{\sqrt{2}}\frac{n_2}{n_1}$, turns ratio of the coupling step-up transformer.
α, phase-shift of the inverter output voltage from the reference position.

4. Proposed control strategy

The proposed control of the three-phase grid-connected TEG system consists of an external, middle and internal level, as depicted in Fig. 5.

4.1. External level control

The external level control (left side of Fig. 5) is responsible for determining the active and reactive power exchange between the TEG system and the utility grid, through an active power control mode (APCM) and a voltage control mode (VCM), respectively.
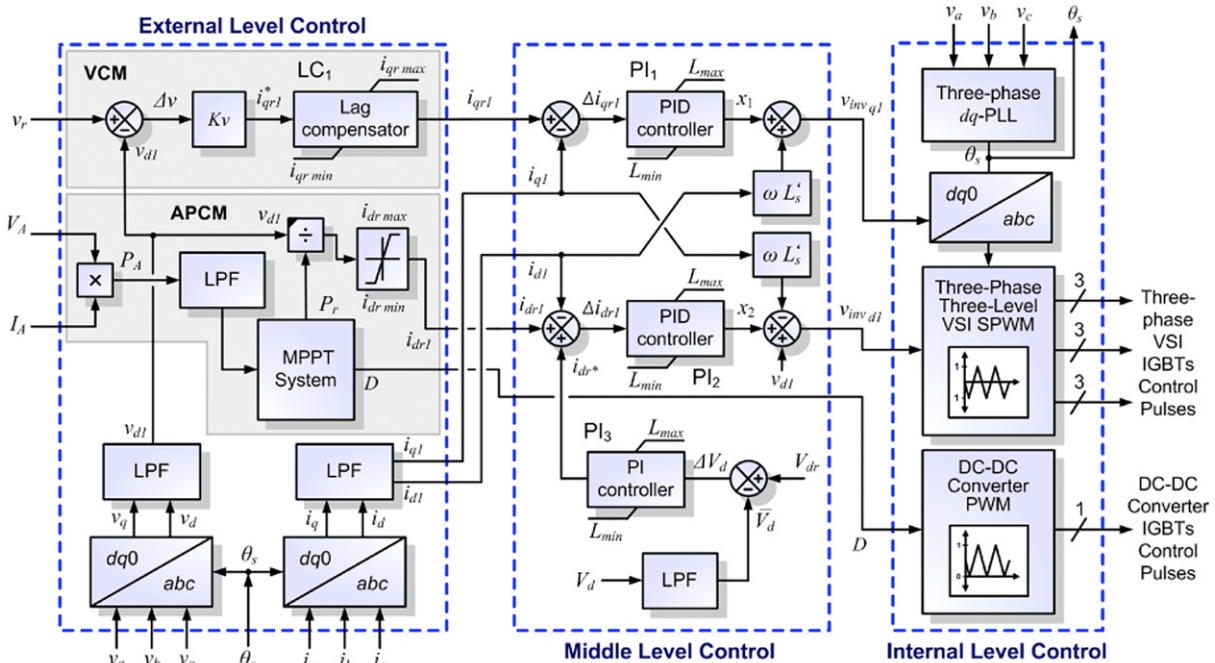

Fig. 5 – Proposed multi-level control scheme for the three-phase grid-connected TEG system.
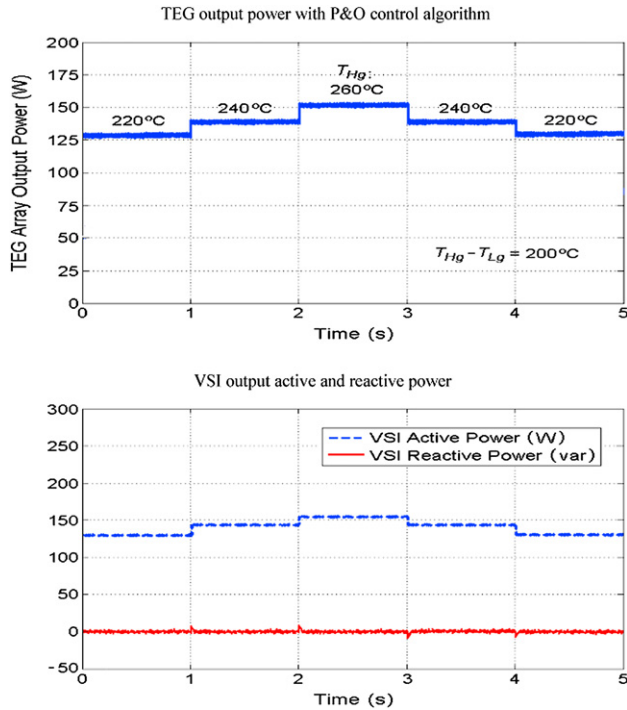
Fig. 6 – Simulation results for active power exchange with the utility grid (APCM).

The main purpose of the grid-connected TEG is to transfer the maximum thermal power into the electric system. In this way, the APCM aims at matching the active power to be injected into the electric grid with the maximum instant power generated by the thermoelectric generator array. This objective is fulfilled with an MPP tracker that employs a ''Perturbation and Observation'' iterative method for adjusting the DC–DC converter duty cycle according to the result of the comparison of successive TEG output power measurements. This control algorithm has widely proved to be very efficient in tracking the MPP of photovoltaic systems [7]. The generated power signal P_r is then converted to a direct current reference (i_{dr1}) for the middle control.

The VCM is designed to control the voltage at the point of common coupling (PCC) of the VSI to the AC grid, through the modulation of the reactive component of the output current (fundamental quadrature component, i_{qr1}). To this aim, the magnitude of the voltage vector at the PCC (v_{d1}) is compared to a voltage reference. An error signal is produced and then fed to a proportional-integral (PI) controller.

4.2. Middle level control

The middle level control makes the expected output to dynamically track the reference values set by the external level (middle side of Fig. 5). In order to derive the control laws for this block, the dynamic model of the VSI described in detail in Ref. [8] is employed. By using two conventional PI controllers with proper feedback of VSI output current components i_{d1} and i_{q1}, yields a resultant model with no cross coupling. It can be also seen the additional regulation of the DC bus capacitors voltage V_d, by using another PI controller which

allows eliminating the steady-state voltage variations as a consequence of changes in the inverter losses.

4.3. Internal level control

The internal level (right side of Fig. 5) is responsible for generating the switching signals for the 12 valves of the three-level VSI, according to the control mode (sinusoidal PWM) and types of valves (IGBTs) used. This level is mainly composed of a line synchronization module, a three-phase three-level SPWM firing pulses generator for the VSI and a PWM generator for the IGBT of the boost DC–DC converter. The line synchronization module consists mainly of a phase locked loop (PLL). This circuit is a feedback control system used to automatically synchronize the device switching pulses; through the phase θ_s of the inverse coordinate transformation from dq to abc components, with the positive sequence components of the AC voltage vector at the PCC.

5. Digital simulations

In order to investigate the effectiveness of the proposed models and control algorithms, digital simulations were implemented using SimPowerSystems of MATLAB/Simulink [9]. For validation of both control strategies, i.e. APCM and VCM of the TEG system, two sets of simulations were carried out.

Simulations depicted in Fig. 6 show the case with only active power exchange with the utility grid, i.e. with APCM activated, for a TEG array composed of a string of 15 HZ-20 TEG modules connected to a 380 V AC system trough a DC–DC–AC
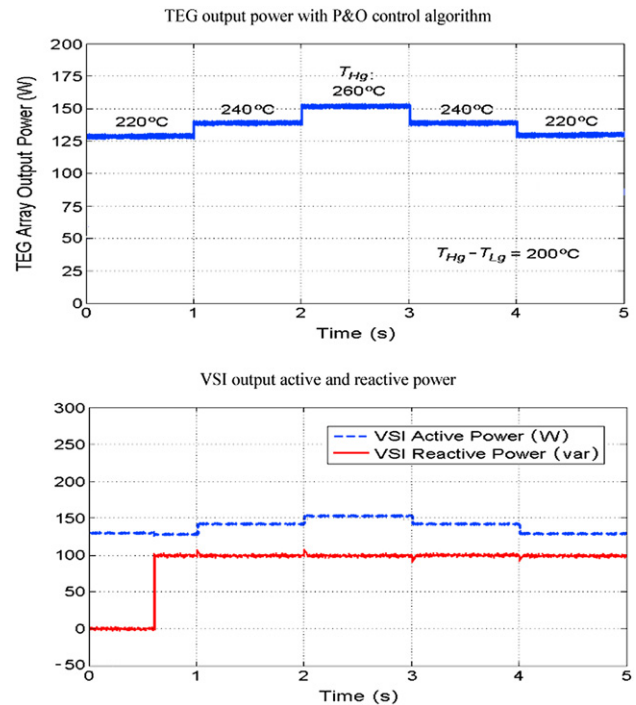

Fig. 7 – Simulation results for active and reactive power exchange (APCM and VCM).

converter. The temperature difference applied to the TEG junctions varies in steps every 1 s as described in the figure (in agreement with Fig. 3), producing changes in the maximum power drawn from the TEG array. As can be observed, independently of the internal resistance of the TEG, the P&O algorithm proves to be accurate in following the MPP of the TEGs, for an optimum duty cycle perturbation step in accordance with the chopper dynamics. As can be noted, all the active power generated by the TEG system is injected into the electric grid, except losses. It can be also seen that no reactive power is exchanged with the electric system.

Simulations of Fig. 7 show the case with active and reactive power exchange with the utility grid, i.e. the APCM is activated all the time while the VCM is activated at $t = 0.6$ s. As can be seen, all the active power generated by the TEG array is injected into the electric grid, except losses. These losses are increased with the generation of 100 var of reactive capacitive power, causing a slightly lower exchange of active power than the previous case studied.

6.   Conclusion

In this paper, the application of thermoelectric generators as a novel technological alternative of distributed generation was analyzed. The full detailed modeling and a new control scheme of a three-phase grid-connected TEG was proposed, incorporating an MPPT for dynamic active power generation jointly with reactive power compensation of distribution systems. Validation of models and control schemes was performed by using digital simulations. Moreover, a small-scale

TEG experimental set-up was employed to demonstrate the accuracy of proposed models.

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